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BNL-29779

CONF-810831--50

THERMAL CONDUCTIVITY MEASUREMENTS OF INSULATORS FOR FUSION BLANKETS**

F. L. Horn, J. A. Fillo, and J. R. Powell

Brookhaven National Laboratory
Upton, New York 11973 U.S.A.

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Alumina-silica mat (8 lb/ft²) varied in thermal conductivity in air and Ar from 0.06 W/m-K at 300°C to 0.22 W/m-K at 1000°C, but in He it increased to 0.24 W/m-K at 300°C and 0.54 W/m-K at 1000°C, while in steam it was about midway between these values. The carbon and graphite felts behaved similarly, but the rigid and denser (24 lb/ft²) zirconia fiberboard exhibited superior insulating properties: 0.07 W/m-K at 300°C and 0.14 W/m-K at 1000°C in air and Ar, and 0.13 W/m-K at 300°C and 0.17 W/m-K at 1000°C in steam, but rising to 0.15 W/m-K at 300°C and 0.49 W/m-K at 1000°C in He. The lighter zirconia felt (14 lb/ft²) in steam at 1000°C was thought to be best at 0.23 W/m-K and only 0.40 W/m-K in He at 1000°C.

1. INTRODUCTION

The unique feature of fusion neutrons, namely long-range penetration in matter and deposition of energy deep inside reactor blankets, can be used to generate very high temperatures for high-efficiency hydrogen production processes as well as high efficiency electrical generation. The interior of the blanket can be kept at much higher temperatures than the first wall and module structure, if the latter is thermally insulated from the interior and cooled by a separate coolant circuit.

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Several blanket concepts have been proposed, all of which have as general design objectives the two following features: a) capability to process heat at temperatures $\geq 1000^\circ\text{C}$, i.e., achieving maximum fraction of nuclear heating in the high-temperature zone and maximum blanket energy multiplication; and b) breed enough tritium to sustain the DT fuel cycle.

The direct heating of steam in high-temperature blanket interiors for high temperature electrolysis process heat applications places design constraints on both the portion of the blanket that generates the high-temperature steam, as well as the reactor system as a whole. Tritium cannot be bred inside the high-temperature steam cooled region of the blanket modules. Not only would it be impractical to extract it from the H₂ product (which would have objectionably high

tritium levels) but the steam would chemically react with whatever lithium material was used for tritium breeding. Separate tritium breeding modules must be introduced.

The steam coolant must be prevented from leaking to the plasma chamber by some type of vacuum/coolant structural pressure boundary. The top working temperature of the first wall structural metal is in the range of -300° to 500°C , depending on material, wall thickness, blanket module size, and internal pressure. Because of the temperature limitation, the metal structure must be cooled by a separate coolant circuit (e.g., water) which operates at a considerably lower temperature than the high temperature (1000°C - 1400°C) steam cooled interior.

Blanket designs of the low-temperature structure/hot interior concept were first proposed in connection with studies on minimum activity blankets using an aluminum structure.⁴ A conceptual synfuel blanket module design is shown in Figure 1.

The first wall intercepts the charged particle energy and x-radiation and removes its heat. The neutron/gamma energy deposited interior to the blanket is used to raise the high-temperature steam. A good thermal insulator is required between the hot interior and the cool structure in each blanket module. This material must be compatible with both the steam coolant and the refractory interior. The most promising insulator option is to use the same material as used in the interior, e.g., ZrO₂ or Al₂O₃, but in a low density form perhaps as a fibrous layer. The key questions are the long-term stability of the thermal insulator and integrity of the oxide interior in a steam atmo-

**Work performed under the auspices of the U.S. Dept. of Energy, Washington, DC 20585

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Figure 1 : HTE process module 5000 MW reactor

sphere with radiation exposure and possible thermal cycling.

Materials experiments⁶ indicate that ZrO_2 and Al_2O_3 are suitable for long-term service up to $1500^\circ C$ (the present experimental limit at BNL) in steam, steam plus hydrogen, and CO_2 process streams. Experiments with SiC and MgO indicate that these materials are restricted to somewhat lower temperatures.

Blanket applications for high-efficiency electrical generation⁷ would use inert gas coolants (e.g., He or Ar) and refractory interior (e.g., graphite, oxides, or carbides) thermally insulated from the cooler structural shell as discussed above. Blanket interior would be in excess of $1000^\circ C$.

Blanket designs for tritium breeding⁸ and extraction by helium purge streams have been designed based on the two-temperature-zone concept, and require thermal insulators to perform in the 600° to $800^\circ C$ range.

In summary an insulating material must satisfy a number of requirements and constraints. For example, it must show a high resistance to radiation damage, maintain structural integrity, and more importantly, have a low thermal conductivity to minimize heat leakage between the hot interior and cooler structural shell. Ideally, heat leakage between the two regions should be kept to a few percent of the energy deposited in the hot interior. Lastly, a good insulator should exhibit low density to minimize internal heat generation within it, and at the same time be compatible with the coolant shield with which it comes in contact.

2. EXPERIMENTAL TEST APPARATUS

Thermal conductivities of five candidate insulating materials were determined in the temperature range of 300° to $1000^\circ C$ in air, argon, helium and steam at one atmosphere pressure. Tests were carried out in a non-nuclear environment, and the results compared to manufacturer's and other existing data where available as a

check on the operation of the apparatus.

The test apparatus was an insulated cylindrical shell with coolant flowing through tubes attached to the outside of the shell, Figure 2.

Figure 2 : Test apparatus in box enclosure

The insulation to be tested was one of the layers of insulation that lined the inner part of the shell, all of which was heated along the axis of the cylinder with a single electric rod heater, Figure 3.

Figure 3 : Rod heater in test apparatus

Axial temperature gradients were minimized to assure radial heat flow so that the thermal conductivity could be determined by the equation:

$$Q = \frac{(2.73) (L) (K) (\Delta T)}{\log_{10} \frac{D_1}{D_2}} \quad (1)$$

where:

- Q = heat transferred,
- K = thermal conductivity of test specimen,
- L = length of insulation,
- Δt = temperature difference across insulation,
- D_1 = outer diameter of insulation, and
- D_2 = inner diameter of insulation.

The temperature difference was measured by thermocouples placed at the inner and outer surface of the insulation. The heat transferred to the shell was calculated knowing the flow rate of the coolant flowing through the attached tubes and the difference between the inlet and outlet coolant temperatures. The thermal conductivity was then calculated by Eq. (1) using the average specific heat of the coolant. The coolant was water when the insulation was exposed to either helium, argon, or air and ethylene glycol when the insulation was exposed to steam.

In practice four layers of half-inch thick insulation were used to line the cylinder with twenty-two type-K thermocouples placed in four quadrants between the layers. The temperature differences for each quadrant were averaged for the final calculations. Heat leakage from the ends of the insulation was minimized by placing three layers of reflective aluminum foil at each end.

TEST RESULTS

The results of many runs with alumina-silica mat in air were found to agree well with the manufacturer's thermal conductivity data⁹ (Figure 4) particularly at the higher temperatures of interest. Data on alumina-silica mat were high by an average of 4.1% in the 400 to 1000°C range. Results of the alumina-silica mat in argon showed very little difference from the results in air. As a consequence of the higher thermal conductivity of helium compared with air and argon, at any temperature, the thermal conductivity results for the alumina-silica mat in helium show a large increase compared with those in air. The results are about two and one-half times as high as those in air at 800°C. The results in steam lie midway between the air-argon and helium results again due to the higher thermal conductivity of steam compared with air.

Carbon felt³ was tested in both argon and helium (Figure 5). The results in argon were similar to the alumina-silica results, and the thermal conductivity in helium was about double that for argon. The thermal conductivity results of the lower density graphite felt¹⁰ were very similar to those of the carbon felt (Figure 6). The densities shown in the Figures and in Table 1 are manufacturer's "nominal" densities. Again, the results in steam showed a thermal conductivity between those in argon and helium. As a

Figure 4 : Thermal conductivity of alumina-silica mat in helium, argon, air, and steam

Figure 5 : Thermal conductivity of carbon felt in helium and argon

check on Eq. (1) and the method to determine thermal conductivity, carbon felt was also tested in combination with the alumina-silica mat. That is, using the known values of thermal conductivity for the alumina-silica mat and the respective temperature difference

Figure 6 : Thermal conductivity of graphite felt in helium, argon, and steam

across each insulation layer, the thermal conductivity of the carbon felt was calculated by the following equation:

$$\frac{K_1}{K_2} = 1.456 \frac{\Delta t_2}{\Delta t_1} \quad (2)$$

Figure 7 : Thermal conductivity of zirconia fibrous insulation board in helium, argon, air and steam

where the constant accounts for the difference in a cylindrical geometry between the two contacting layers of insulation. The thermal conductivity calculated by Eq. (2) gave identical results to the heat measurement method, Eq. (1).

The higher density zirconia fiberboard was fabricated into a cylinder and tested in combination with alumina-silica mat (Figure 7). The zirconia was phase-stabilized with 8% yttria and the 5 μ fibers bonded with 5% zirconia silicate. The thermal conductivity results in air again closely followed the manufacturer's data data¹¹. The test results in argon were similar to those in air; however, the thermal conductivity in helium was the lowest of the materials tested. At 300°C it was 40% lower than the alumina-silica mat and carbon felt. At 800°C the thermal conductivity of the zirconia board was still 17-20% lower than that of the alumina-silica mat and the carbon or graphite felt in helium. In steam the fiberboard had a thermal conductivity only 21% more than in air-argon at 1000°C and 50% of the values for alumina-silica and for graphite felt.

The less dense zirconia felt was also tested in air, argon, and steam and the results generally followed the manufacturer's data¹² (Figure 8). The results in helium at 400°C indicated a 21% higher thermal conductivity than the zirconia fiberboard, but at 800°C the felt and board thermal conductivities were about the same (0.335 vs. 0.350 W/m·K, respectively). The results in steam were not as low as the fiberboard, but they were considerably lower (40%) than for alumina-silica, and graphite felt.

Figure 8 : Thermal conductivity of zirconia felt in helium, argon, air, and steam

The thermal conductivity tests in helium were limited to temperatures on the order of 800°C due to the power requirements of the heater. The data were extrapolated to obtain the 1000°C values shown in Table 1. At this temperature, the zirconia felt is the lowest at 0.40 W/m-K and the alumina-silica mat the highest at 0.54 W/m-K; while the other three varied from 0.49 to 0.51 W/m-K and are within their probable errors of each other.

TABLE 1
THERMAL CONDUCTIVITY OF INSULATORS IN THE
TEMPERATURE RANGE OF 300° TO 1000°C

	W/m·m ⁻¹ ·K							
	AIR 100 1000	ARGON 100 1000	HELIUM 100 1000	100 1000	100 1000	100 1000	100 1000	100 1000
ALUMINA-SILICA MAT 8700 /ft ²	06	22	07	28	24	34	.17	.36
CARBON FELT 5700 /ft ²	—	NA	.11	29	24	31	—	—
GRAPHITE FELT 4700 /ft ²	—	NA	.11	27	26	31	.17	.36
ZIRCONIA FIBROUS BOARD 24700 /ft ²	07	14	07	14	15	49	.18	.17
ZIRCONIA FELT 14700 /ft ²	08	17	08	17	18	40	—	.23

4. DISCUSSION OF RESULTS AND MAIN CONCLUSIONS

The thermal conductivity of any of the insulating materials was markedly increased when tested in helium due to the greater conductivity of the interstitial gas. An exception to this would be a totally closed cell material with total impermeable cell walls, but such a material is not known at present.

The helium pressure in a fusion blanket will be on the order of 50 atmospheres, a value much greater than the one atmosphere in which the tests were conducted. On the other hand, the high pressure environment will have little additional effect on those insulating materials whose pore size is already greater than the mean free path of the gas at one atmosphere which was the case for the materials tested.

In steam the low thermal conductivity of zirconia felt and board would have to be balanced against their greater density, but the zirconia felt appears better than the alumina-silica mat even with its lower density.

Of the materials tested, all have satisfactory thermal conductivity values in the temperature range of interest and would be acceptable for blanket applications.

In conclusion, a material to be used for insulation in a fusion blanket module should show high resistance to radiation damage, maintain its structural integrity, and more importantly, have a low thermal conductivity combined with a low density to minimize internal heat generation. The zirconia felt has the lowest thermal conduc-

tivity at 1000°C but its density is three times that of the carbon felt and two times the alumina-silica mat density. The graphite felt, with 25% more thickness, would give equal insulating properties in helium to the zirconia felt, and the increase in weight would still make it one of the lightest of the insulations; therefore, at this point, graphite felt would be the preferred insulation in helium, and zirconia felt in steam.

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